

Enhanced Damage in Bipolar Devices at Low Dose Rates: Effects at Very Low Dose Rates*

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Abstract - *The effect of very low dose rates and equivalence of high-temperature irradiation are investigated for several device types that are sensitive to enhanced low dose-rate damage. New results are included at 0.001 rad(Si)/s.*

Introduction

The increased damage exhibited by some types of bipolar devices under low dose-rate conditions is extremely important for space applications. Several laboratories have investigated this phenomenon during the last three years.[1-6] Enhanced damage has been observed in a number of different circuits and device technologies, and work is continuing to better understand the underlying mechanisms. Thus far no practical alternative to low dose-rate testing has been found, although irradiations at elevated temperature increase the damage at high dose rate,[3,4] and may ultimately prove useful as a screening or testing method.

Further complicating this issue are differences in fabrication methods and device structures that are used in different bipolar technologies, along with the fact that specific circuit design techniques can mask or enhance the effect of changes in internal transistor gain on the net electrical properties of the circuit. This paper adds additional information to the low dose-rate problem in bipolar technologies, presenting data at dose rates as low as 0.001 rad(Si)/s. New results are reported for devices with super- β transistors, as well as for devices with integrated JFETs. The effect of elevated temperature irradiation on dose-rate effects is also investigated for specific device types that exhibit very large enhanced damage factors at low dose rate.

Fabrication Technologies and Circuit Design

A number of different methods are used to fabricate bipolar devices. These fabrication methods affect not only geometry and doping levels, but also the oxides that are present in the vicinity of the emitter-base junction of bipolar transistors. Older linear ICs use a thick isolation oxide that covers the entire wafer, and is subject

to all high-temperature processing and diffusion steps except the formation of the buried layer. Newer devices with oxide sidewall isolation use a locally grown oxide for surface isolation, similar to the field oxide used in CMOS technologies, and trench isolation for lateral isolation of the collector.

These fabrication differences further complicate the problem of enhanced low dose-rate damage. Some technologies are no longer sensitive to dose-rate effects below 10 rad(Si)/s,[7] while others are still affected even below 0.005 rad(Si)/s. The magnitude of the damage also varies with technology. The pnp transistors in older devices may degrade by a factor of ten or more at 10 krad(Si), while other device types in newer technologies may have relatively small changes in gain, even at levels above 100 rad(Si).

Differences in circuit design can have a large influence on the importance of dose-rate effects on specific devices. For operational amplifiers and comparators with basic input designs, changes in input bias current approximately track gain degradation of the input transistor. However, many linear devices use more complex designs, causing critical input parameters to depend on matching of several different transistor types in the input stage. Such designs may exhibit nonlinear changes with increasing levels of radiation, as well as much larger unit-to-unit variability in radiation behavior than more basic designs. For example, Figure 1 shows the dependence of input bias current of the OP-27 op-amp on total dose at a high dose rate. The input current depends on the balance between an internal current source, using lateral pnp transistors, and the base current of the npn input transistor. One of seventeen units that were tested exhibited a very large change in bias current at low total dose levels. It is likely that this unit would exhibit even more difference from "typical" devices under low dose-rate conditions, where pnp degradation is typically much larger than that of npn devices. The point is that linear integrated circuits are complex

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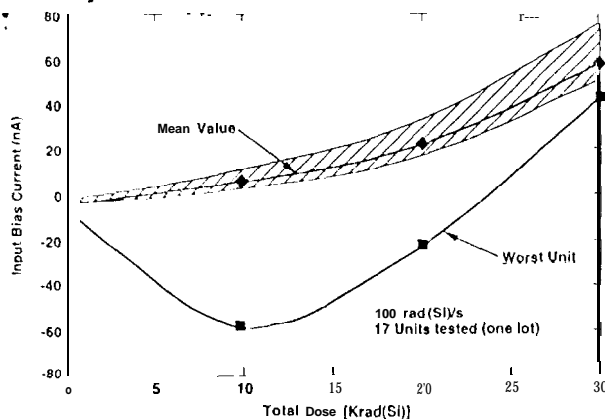


Figure 1. Effect of Total Dose on Input Bias Current of 0127 Comparators at High Dose Rate

devices. It may be difficult to interpret the effects of enhanced damage on their performance because of circuit design factors, even if the basic behavior of internal transistors is well understood. Circuit effects are closely linked with the enhanced damage problem, particularly for linear integrated circuits.

New Results at Very Low Dose Rate

The 108A is a precision op-amp with low input offset current and bias current that is widely used in space systems. Tests of the 14108A op-amp at high dose rate have shown that only slight parametric changes typically occur, and that input offset voltage and output drive current remain within acceptable limits even at 100 krad(Si). However, recent tests at very low dose rate show that the input currents of the 1M108A, which primarily depend on the gain of the input super- β transistor, are also affected by dose rate. When the change in input bias current is plotted vs. total dose, the slope increases at high total dose levels. As shown in Figure 2, this slope change occurs at much lower levels when the device is tested at low dose rates. At 0.002 rad(Si)/s, the slope change occurs at approximately 10 krad(Si). (These tests are still in progress, and will be extended to > 40 krad(Si) for the final paper, along with results for a second manufacturer). The change in slope magnifies the effect of increased damage at low dose rates on this device.

Special measurement of the internal current source of the 1M108A were also made at various dose rates. The current source uses several different components, including lateral pnp transistors, and its performance may provide insight into internal circuit margins and

performance. that are not evident from measurement of normal input specifications

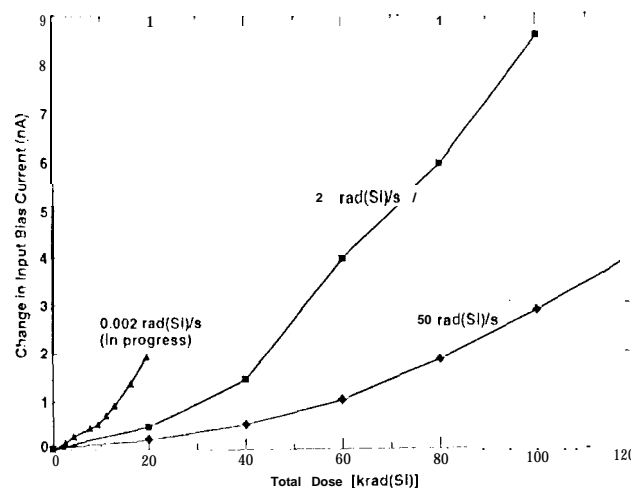


Figure 2. Change in Input Bias Current of the 1M108A vs. Total Dose at Several Dose Rates

Figure 3 compares current source degradation at three dose rates. Degradation is far more severe at low dose rates. The current decreases, lowering the emitter current of the input transistor. Eventually the circuit margin will be affected, which may cause abrupt changes in other parameters, such as input offset voltage and open-loop gain. Current degradation for the second manufacturer at low dose rate was very similar to the results shown in Figure 2; these results will be shown in the final paper, and further analyzed to determine if they are effective precursors of nonlinear or catastrophic circuit performance in these devices.

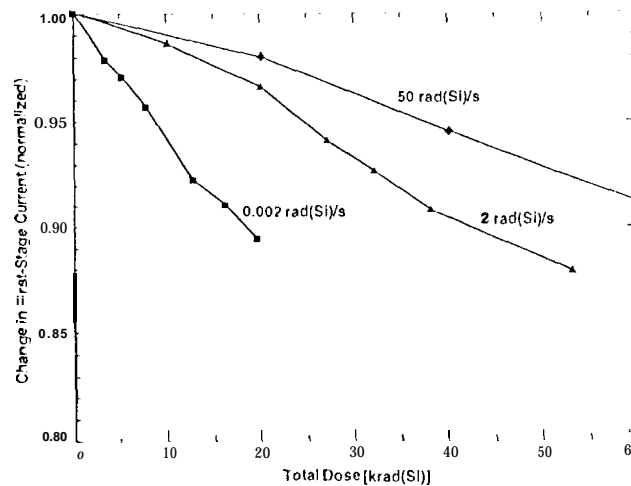


Figure 3. Degradation of the Internal Current Source of the 108A Op-Amp at Several Dose Rates.

Although input bias current is a very useful parameter to evaluate input transistor degradation, it is generally not as important as input offset voltage in typical circuit applications. Figure 4 shows the very large difference in the behavior of input offset voltage of the LM324 at low dose rates. Only slight changes occurred in input offset voltage at 0.005 rad(Si)/s, similar to the results obtained at high dose rate. However, when devices were tested at a slightly lower dose rate, the results were dramatically different. input offset voltage changed by very large values. Additional tests at 0.001 rad(Si)/s are in progress for two different manufacturers of the LM124/324 to extend the data to even lower dose rates, as well as to compare effects in this device from two different manufacturers. Very low close-rate tests are also in progress for a second device type, the OP42 (JFET input), which also exhibited large changes in offset voltage at low dose rates. These results will be included in the final paper, along with an analysis of the circuit design factors that cause such abrupt differences in response at very low dose. rates.

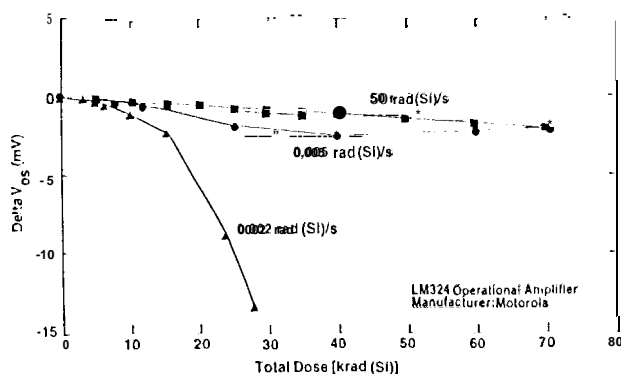


Figure 4. Dependence of Input Offset Voltage of the LM324 Op-Amp vs. Total Dose at Various Dose Rates

High-Temperature Irradiation

Irradiation at elevated temperature increases the damage in bipolar structures that are sensitive to dose. rate, providing a potential alternative to lengthy irradiations at low dose rate. Fleetwood, et al., initially proposed irradiation at 60 °C. [2] More recent work by Schrimpf, et al. investigated a wider range of temperatures, using high dose

rate (100 rad(Si)/s). [3] This work was promising, but the damage continued to increase at elevated temperature, and did not appear to level off, even at 125 °C. This is a very high temperature, which is beyond the temperature rating of some parts that are now being considered for future space applications. It is possible that even higher temperatures may be required for other processes.

One alternative is to irradiate devices at a somewhat lower dose rate. This may allow a lower temperature to be used, while still allowing tests to be completed in hours or days instead of the months that are required to do tests at very low dose rates. In order to investigate this, a series of experiments were done using LM111 comparators manufactured by National Semiconductor. These devices have been shown to have a very strong dose-rate dependence, with the additional advantage that very simple measurements can be used to determine the gain of the substrate pnp input transistor. Two devices from the same lot were irradiated under each condition. Results of the pairs of devices generally agreed within about 10%.

Figure 5 shows the effect of irradiating devices at a more modest close rate, 6 rad(Si)/s, at various temperatures. Low dose-rate data (at room temperature) is also shown for comparison. Irradiations at 60 °C are still well below the low close-rate results, but irradiating the devices at 90 °C predicted results that are reasonably close to the data at low close rate.

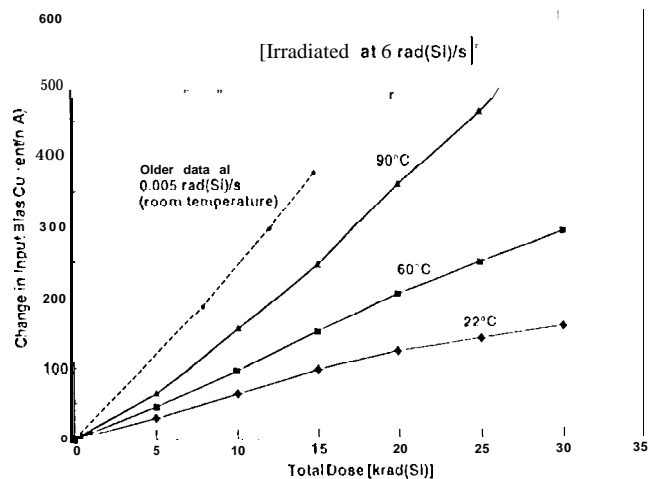


Figure 5. Effect of Irradiation Temperature on Input Bias Current of LM111 Comparators with Irradiation at 6 rad(Si)/s

A series of irradiations at 90 °C were done at several dose rates in order to investigate dose-rate dependence. These results are shown in Figure 6. The damage is much lower at 50 rad(Si)/s, and clearly this temperature is far too low to allow reasonable simulation of low dose-rate effects. The damage is much larger at 6 rad(Si)/s, and it is only slightly greater at 1 rad(Si)/s. This suggests that the temperature dependence is beginning to level off, and that it may be possible to use lower dose rates and more modest temperatures to simulate effects at low dose rate.

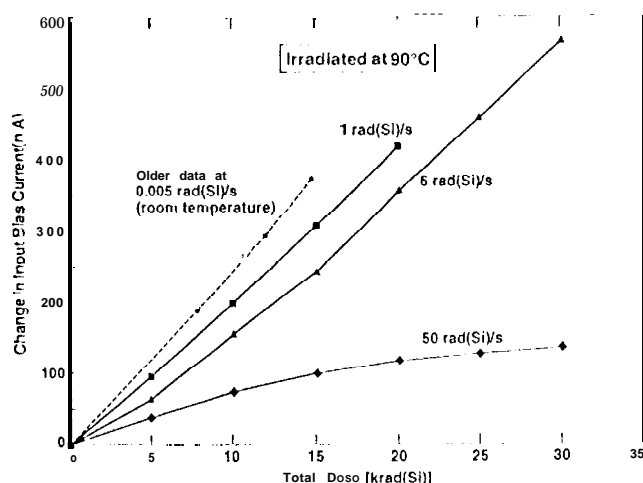


Figure 6. Effect of Different Dose Rates on LM111 Comparators Irradiated at 90 °C

Discussion

Although the initial results are promising, high-temperature irradiation adds still another dimension to a complex technical problem. The equivalence of high-temperature irradiation and irradiation at low dose rate must be carefully evaluated before high dose-rate irradiations can be used. It is also possible that the appropriate temperature and dose rate may depend on the specific process. It may also work for only some processes. Nevertheless, it remains an intriguing technique with high payoff if it can eliminate the need for extremely lengthy irradiations. The current interest in commercial technologies and the possibility that devices with plastic packages may eventually be used in space provide added impetus to investigating the feasibility of using temperatures well below 125 °C for damage acceleration.

Extending low dose-rate results at room temperature to even lower dose rates is also important. Some devices clearly remain sensitive

to dose-rate effects even at dose rates in the range of 0.002 to 0.01 rad(Si)/s. It is important to determine how low the dose rate must be in order for damage to be independent of dose rate. It is also important to determine why some devices, such as the LM324, exhibit such large differences in response with relatively small changes in dose rate. It is unlikely that large differences are occurring in gain degradation. However, it is important to improve our understanding of circuit-related factors that can apparently enhance the importance of small differences in gain degradation. This will be discussed in detail in the full paper.

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